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STRUCTURAL STABILITY OF A CAST Co-Cr-Mo ALLOY DURING IMPULSIVE THERMAL-MECHANICAL LOADING

TECHNICAL REPORT

William T. Ebihara

December 1970

SCIENCE & TECHNOLOGY LABORATORY

RESEARCH & ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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34

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DA 1T061102B32A AMS Code 501B.11.85500.01

ABSTRACT

The response of a cast cobalt-base alloy to impulsive thermal-mechanical fatigue conditions, present during the firing of automatic weapons, was examined. The study indicates that a variety of structural alterations take place near the interior gun bore surface that are dependent upon the firing schedule and the ammunition used. Surface-layer melting and Stage I type of fatigue cracks are noted for the larger caliber inserts. Extensive slip-deformation and work-hardening in the surface areas were attributed to the interior ballistics conditions as well as to the prior machining operations. The stress-induced transformation phenomenon in the matrix and the precipitation in the slip zones related to the enhancement of wear resistance are discussed.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

INTRODUCTION

The application of improved materials to military hardware for which the U. S. Army Weapons Command has responsibility is one of the missions of the Science and Technology Laboratory of this Command. For compliance with this goal, an effort was made to structurally analyze a breech liner-material, Haynes Stellite Alloy No. 21, which has been utilized in numerous small caliber weapons for more than twenty-five years. Despite the extensive usage of this alloy, relatively few analyses have been undertaken to define the reasons for its satisfactory performance. Further, little effort has been expended to improve the alloy through compositional and structural modifications. The purpose of this initial study was to describe the behavior of the cast alloy in its response to the impulsive thermal-mechanical and corrosive loading conditions of actual test firings. This description will lead to laboratory tests designed to isolate features or processes that control the deterioration mechanisms of this alloy. The ultimate aim of this work is to obtain improved alloys for use in small caliber weapons.

The attractive features attributed to this particular alloy are resistance to chemical attack by hot powder-gases, retention of hardness and strength at elevated temperatures, and excellent wear and abrasion resistance. The major limitation of Alloy 21 lies in its relatively low melting-point range of 1280° to 1350°C. Thus, these inserts are not widely used in weapons requiring double-base propellant powder for increased projectile velocity.

Alloy 21 has the following nominal composition in weight percentage: 28 Cr, 2 Ni, 6 Mo, 0.25 C, and the remainder being Co. The investment-cast alloy has, as its primary matrix phase, a cobalt-rich solid solution with a face-centered cubic structure. Numerous small, well-distributed areas of eutectic carbides are noted in the structure. The binary eutectic is the M_6C type, whereas the ternary form includes the M_6C, the Cr_7C_3, and-or the $M_{23}C_6$ phases (where M represents any carbide forming element).

The fcc matrix found in the as-cast structure is metastable. Correspondingly, the hcp→fcc inversion is quite sluggish at temperatures near 800°C. However, mechanical working at room temperature facilitates the martensitic transformation of the fcc structure to the hcp form.[1]

The alloy, possessing a low stacking-fault energy, exhibits a high propensity to work hardening. However, the casting can be readily machined to close tolerances with

carbide-tipped tools. The insert liners used for the 7.62mm automatic weapon were 6 inches in length and had a wall thickness of approximately 0.10 inch. A schematic drawing of such an insert is shown in Figure 1.

Observations made on the structural appearance of the cast cobalt-alloy, after being subjected to repeated impulsive loading-conditions of actual firing are presented in this report. Although an effort was made to rationalize the causes for the resultant structure, the analyses are considered preliminary. The description of the post-fired cast inserts could eventually lead to the development of better materials for increased service life of rapid-fire weapons.

EXPERIMENTAL PROCEDURE

The 7.62mm machine gun barrels containing the cast Alloy 21 inserts were test fired at a range of approximately 650 rounds per minute. Total firings of 1, 100, and 3000 rounds were obtained. Other gun barrels that had been removed from the test because of loss of accuracy and projectile velocity were examined. Analyses were also performed on eroded caliber .50 and 20mm lined machine gun barrels.

Firing schedules for the 7.62mm and the 20mm gun barrels are given in Appendix A. No information on the firing schedule could be obtained on the caliber .50 gun barrel. The types of ammunition used for the various weapons are listed in Appendix B.

The gun barrels including the cast insert were sectioned longitudinally. Transverse sections were taken at an area approximately one inch forward of the origin of rifling. Longitudinal sections for analyses consisted of areas including the bullet seat to a location of 0.75 inch forward of the origin of rifling. Certain specimens were sectioned and polished at a low angle to the bore surface to provide for a larger viewing area of the damage zone.

Because the firing conditions were known to cause plastic deformation to the liner material, etching techniques were developed to reveal the resulting slipped structures. Metallographic specimens polished to 0.25 micron alumina were chemically etched in a 92 HCl -5 H_2SO_4 -3 HNO_3 acid solution. Moderate etching times delineated only the carbide and the grain boundaries. Prolonged etching times, however, revealed striations or slip bands caused by plastic deformation. Internal deformation in the cast Alloy 21 produced

by a Rockwell C hardness indent at a load of 150 kilograms, is shown in Figure 2 after chemical etching to exhibit the effectiveness of this technique. A 25-hour aging treatment at 816°C followed by chemical etching may also be used to delineate slipband structures as shown in Figure 3. However, such thermal treatments were generally unnecessary to reveal the deformed structure in this investigation.

X-ray diffraction patterns were obtained from the as-cast, as-machined, and test-fired specimens to determine the crystal structure of the matrix. No attempt was made to identify the precipitate phases. Optical microscopy was used throughout most of the structural analysis as well as limited scanning electron microscopy.

RESULTS

Examination of an unfired 7.62mm insert revealed a plastically deformed structure due to the machining operations performed to impart rifling and to yield proper bore dimensions. The depth of deformation was approximately 0.010 inch as observed metallographically. Some transformation of these surface layers to the hcp structure was expected since particles obtained from cutting operations on the cast alloy revealed beta (hexagonal) X-ray diffraction lines.

No significant structural change was observed after one round had been fired, as shown in Figure 4. After 100 rounds, however, localized shallow surface craters or cracks were observed. Typical surface cracks on the land area located one inch forward of the origin of rifling are shown in Figure 5.

As the firing was continued to 3000 rounds under Schedule A, the slip patterns remained basically unchanged; however, they did become more definite and more dense. Rounding of the land corners was observed (Figure 6) as well as increased crack formation and development. Although cracks have been noted to follow the carbide-matrix boundary, extensive crack propagation through carbides was also observed as typified in Figure 7. These cracks generally followed a direction radial to the bore surface.

A cast insert liner subjected to 3423 rounds under the severe firing condition of Schedule B was analyzed. No evidence of the melting of the bore surface layers could be detected, although extensive chemical reaction and cracking were observed as shown in Figure 8. Copper from projectile cladding was observed to fill surface cracks (Figure 9).

In the same figure, longitudinal cracks as well as radial cracks propagating through the carbide-grain boundary structure were noted. As shown in Figure 10, these cracks either sheared the carbides or continued along the carbide-matrix boundary. The cracks observed at this stage of firing were orthogonal to the bore surface or intergranular.

In the deformed surface layers of the insert (after 3423 rounds), precipitates were observed as shown in Figure 11. Identification of these precipitates was not made, although the precipitates were quite likely to be of the $M_{23}C_6$ type of carbide that forms quite readily on stacking faults.[2] Also, in the same specimen, the layers adjacent to the bore surface showed evidence of recrystallization (Figure 12).

Continued firing of the 7.62mm weapon with the cast insert resulted in increased land wear, chemical attack, deformation, and aging as shown in Figure 13. This particular specimen was subjected to 28,410 rounds of fire (Schedule C). Crack propagation was increased at this point, exhibiting at least the Stage I fatigue type of growth behavior. Gross material removal resulted with the intersection of cracks that propagated either along the grain boundary carbides or on the {111} or (0001) slip planes, as shown in Figure 11.

Structural differences after firing were noted for the cast Alloy 21 inserts used in larger caliber weapons. Analyses on the caliber .50 insert were performed. Although a record of the actual firing schedule was unavailable for this insert, evidences of severe firing practice were noted. Occurrence of melting in the extreme surface layers is shown in Figure 15. Just below this area, structures exhibiting recrystallization or the hcp→fcc reversion were observed (Figure 16).

Areas below the bore surface revealed extensive plastic deformation. Extensive striated structures were observed in the lamellar areas as shown in Figure 17.

Widespread crack development was noted for the larger caliber, 20mm automatic weapon. The structure after 7170 rounds of fire (Schedule D) is shown in Figure 18. This particular sample was sectioned longitudinally and polished at a low angle to exhibit a larger surface area. Surface layer melting, extensive chemical reaction, and aging were observed for this insert as shown in Figure 19.

Although cracks generally appeared to grow radially from the bore surface (shown earlier in Figure 18), continued propagation into the interior exhibited orientations approximately 45 degrees to the bore surface as shown in Figure 20. These cracks progressed transgranularly, following principal slip-plane orientations and changed direction slightly at grain boundaries. Evidence of plastic blunting of the crack tip is shown in Figure 20 as well as in Figure 21. Also, cracking through the carbide particles is noted in Figure 21.

DISCUSSION

X-ray diffraction analysis as well as earlier literature[3] indicated that the matrix of the cast Co-Cr-Mo Alloy 21 consisted primarily of the face-centered cubic phase with a small amount of the hexagonal close-packed structure. During machining, the surfaces layers were believed to be converted to the hexagonal form. Deformation either by machining or by subsequent firing occurred in the {111} planes of the matrix.

Little additional damage to the as-machined structure of the 7.62mm insert was observed after one round. For the particular ammunition used on this weapon, the average peak pressure was 50 ksi with a corresponding flame temperature of 2110°C.

After 100 rounds, surface damage in the form of craters or shallow cracks was noted. The loss of surface carbides and matrix material was believed to be caused by the shearing action of the projectile.

Continued firing to 3000 rounds resulted in cracks at the carbide-matrix boundaries and also in cleavage within the carbides. Also, intrusion formation in the matrix proceeded concurrently with the carbide-cracking reaction. Since the as-machined structure shows an intensive amount of slip, deformation in the form of cracks was unlikely to occur early in the firing sequence. Cobalt and its alloys have low stacking-fault energies and, therefore, have a low capacity for cross slip. Thus, actual deformation strains can be accommodated by separation at the carbide-matrix boundaries or within the carbide itself.

The excellent wear-resistance characteristics of this alloy can be attributed to the hard surface-carbides as well as to the formation of the hexagonal matrix structure. The fcc→hcp transformation was believed to have beneficial

results of (a) increased impact energy dissipation and (b) the formation of a surface with a decreased coefficient of friction as shown by Buckley.[4] Further, the enhancement of elevated temperature strength-properties could be attributed to the carbide precipitation on slip planes or on stacking faults.

Prolonged firing schedules on 7.62mm inserts resulted in gross material-loss as a result of the intersection of transgranular cracks as well as of intergranular cracks.

Test firing with double-base propellants for the larger caliber weapons resulted in incipient melting in the surface layers. Extensive chemical reaction was also observed in the surface areas of the caliber .50 and the 20mm inserts. The primary difference between the larger caliber inserts and the smaller 7.62mm insert, aside from surface melting, was that of the orientation of cracks. The larger caliber inserts exhibited cracks typical of Stage I fatigue cracks. Cracks in these inserts were observed to proceed at orientations approximately 45 degrees to the bore surface. Most cracks observed in the 7.62mm inserts were either orthogonal to the surface or proceeded along the grain boundary carbides. Cracks following the Stage II mode, i.e., fatigue failure by cracks orthogonal to the stress direction, were not observed in any of the inserts.

Stage I cracks in the larger caliber inserts exhibited forms typical of the plastic "blunting" process.[5] In this process, the striations such as those exhibited in Figures 20 and 21 are formed as a result of cyclic loading-unloading processes. Cracks were propagated by this process during the tensile part of the fatigue cycle and were followed by resharpening of the crack in the compression part.

CONCLUSIONS

1. Slip deformation and work hardening of the surface layers are attributable to firing as well as to prior machining operations.

2. Cratering or shallow crack-formation caused by carbide and matrix material pullout occurs quite early in the firing sequence.

3. Intergranular crack-propagation follows the carbide-matrix boundary and also cleaves the boundary carbides.

4. Gross material removal is caused by the intersection of transgranular and intergranular cracks.

5. Deformation of the bore surface layers causes the formation of the hexagonal phase.

6. Precipitation in the deformation bands enhances the elevated temperature strength of the alloy.

7. Stage I type of fatigue cracks occurs during test firing of the caliber .50 and 20mm inserts.

8. Surface layer liquation of the larger caliber inserts is attributable to the hotter double-base propellants used in these weapons.

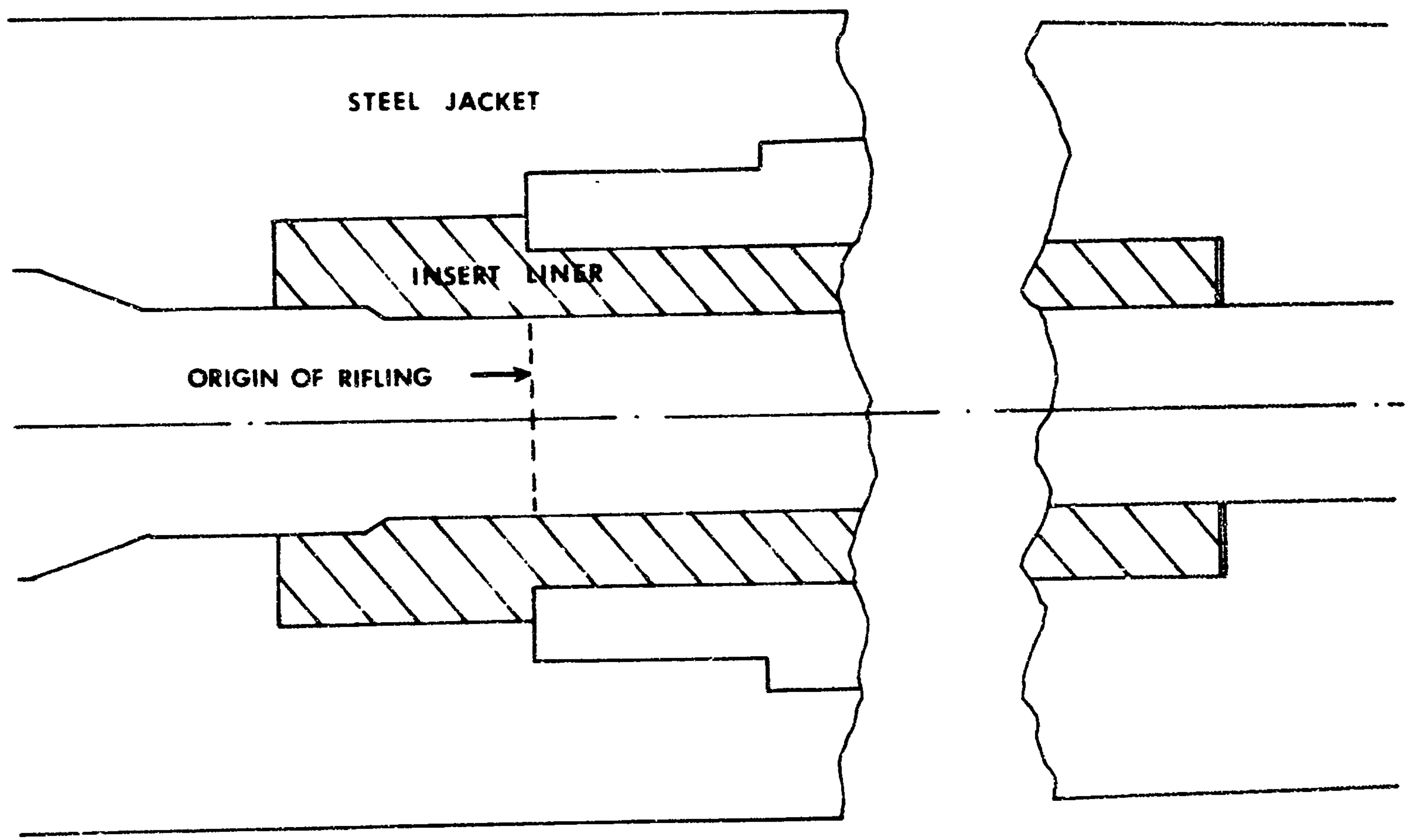

FIGURE 1 SCHEMATIC DRAWING OF 7.62MM INSERT LINED BARREL
Scale: 4/1

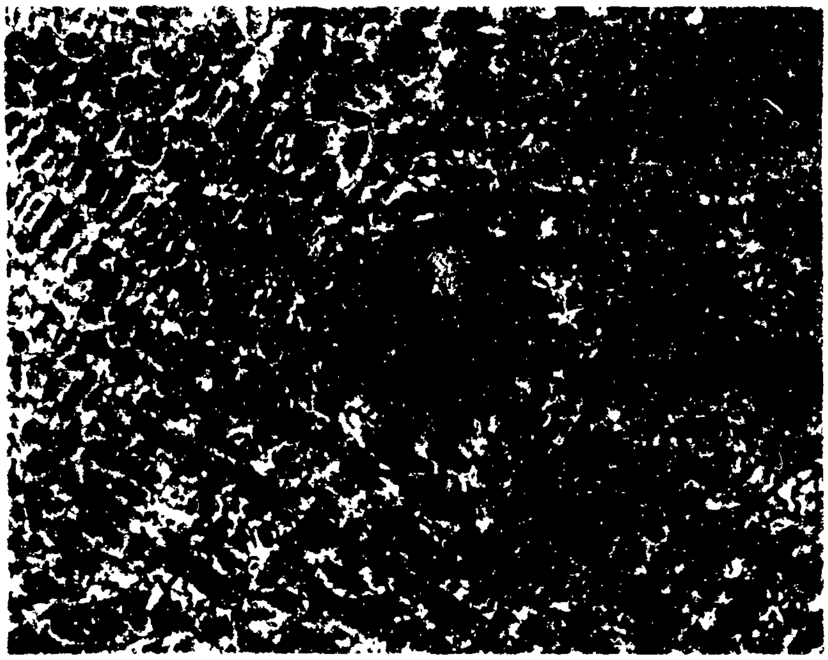

FIGURE 2 EFFECT OF A 150 KILOGRAM ROCKWELL C HARDNESS INDENTATION ON THE CAST STRUCTURE

FIGURE 3 THE EFFECT OF A 25-HOUR AGING TREATMENT AT 816°C ON THE DEFORMED STRUCTURE GENERATED AFTER 3423 ROUNDS OF FIRE

FIGURE 4 MICROSTRUCTURE OF THE LAND AREA AFTER ONE ROUND

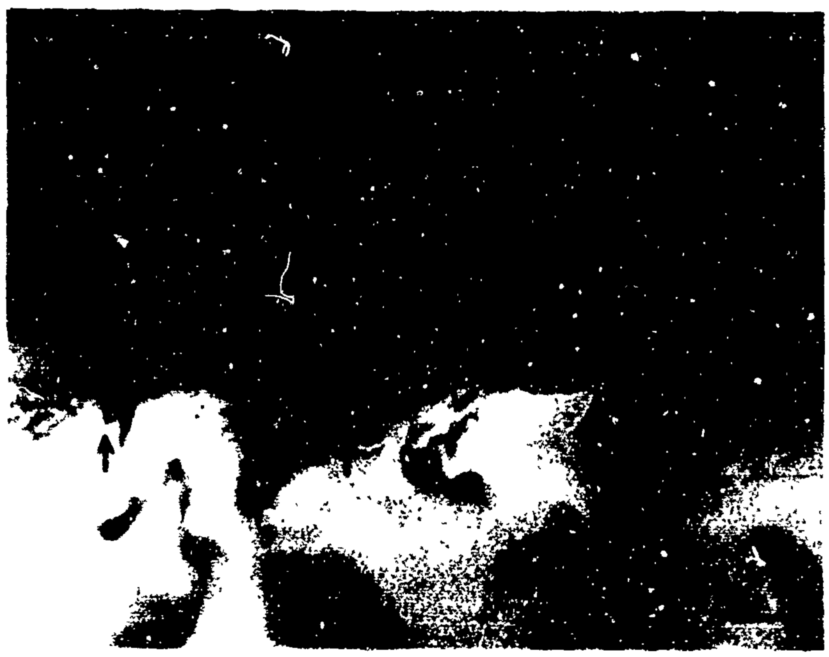

FIGURE 5 MICROSTRUCTURE SHOWING CRACK INITIATION SITES ON LAND SURFACE AFTER 100 ROUNDS

FIGURE 6 MICROSTRUCTURE OF THE LAND AREA AFTER 3000 ROUNDS

FIGURE 7 PHOTOMICROGRAPH SHOWING CRACK PROPAGATION THROUGH CARBIDES AFTER 3000 ROUNDS

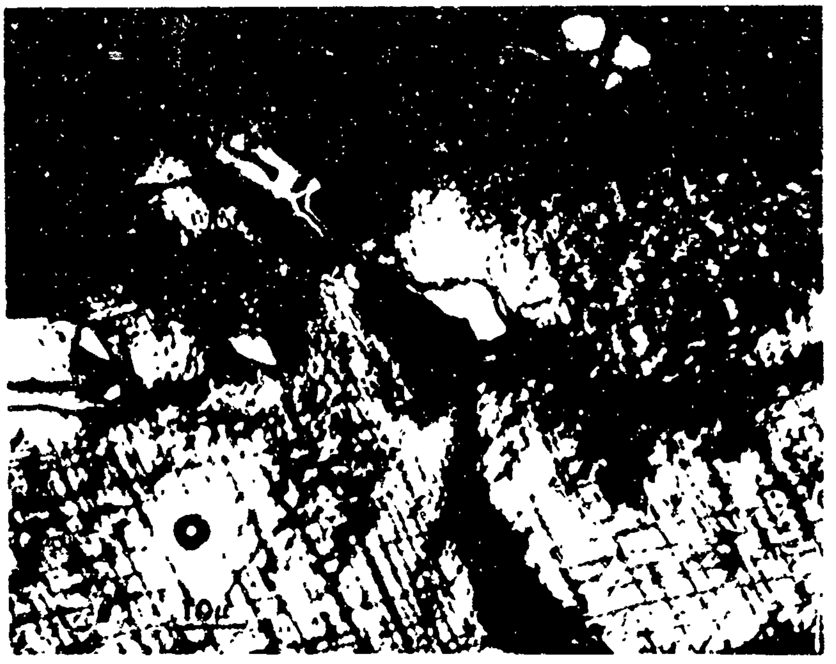

FIGURE 8 MICROSTRUCTURE NEAR THE BORE SURFACE AFTER 3423 ROUNDS

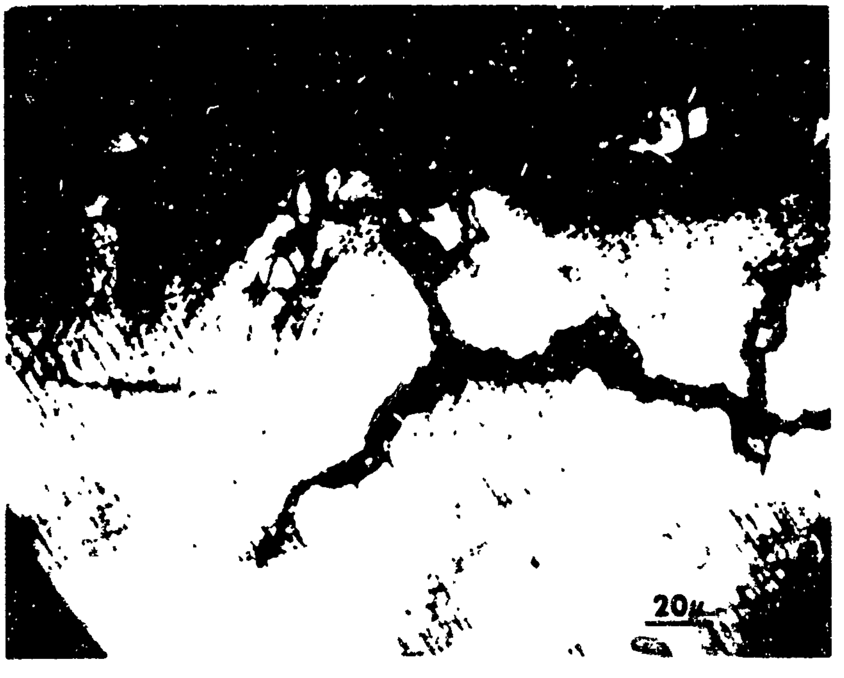

FIGURE 9 MICROSTRUCTURE OF THE BORE AREA SHOWING COPPER IMPREGNATION AND CRACK PROPAGATION

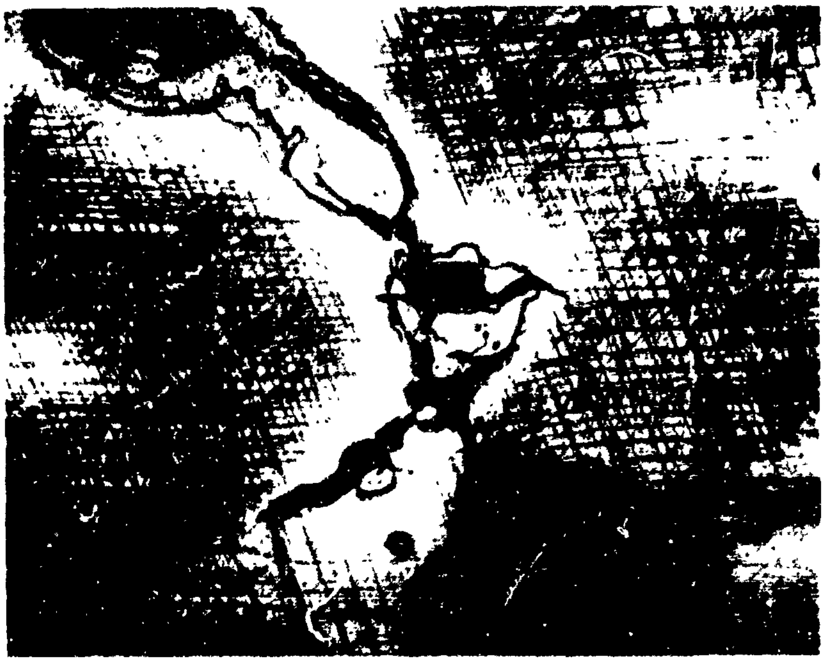

FIGURE 10 PHOTOMICROGRAPH SHOWING CRACK GROWTH THROUGH CARBIDES AND ALONG THE GRAIN BOUNDARY AFTER 3423 ROUNDS

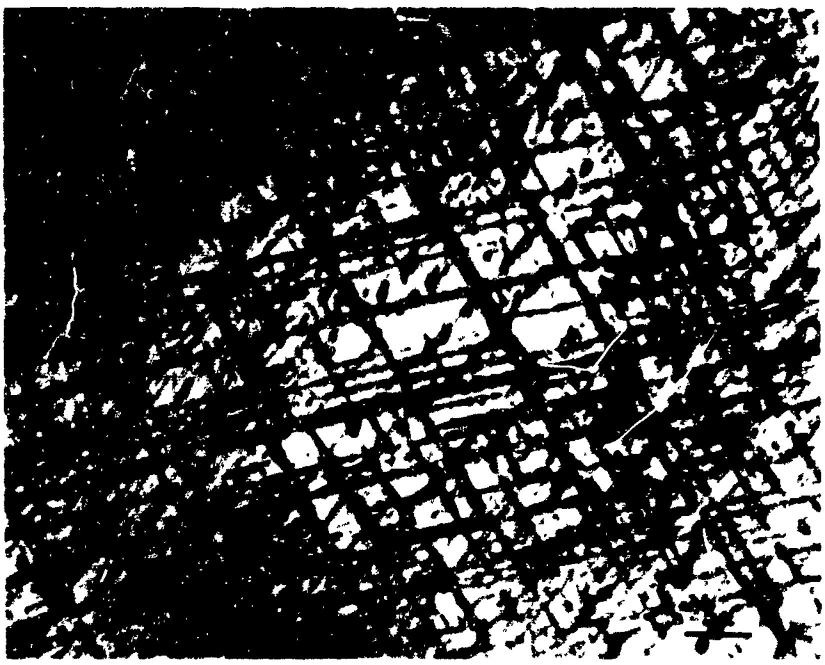

FIGURE 11 MICROSTRUCTURE SHOWING PRECIPITATES IN THE DEFORMED STRUCTURE AFTER 3423 ROUNDS

FIGURE 12 SCANNING ELECTRON PHOTOMICROGRAPH OF LAND AREA AFTER 3423 ROUNDS SHOWING EVIDENCE OF RECRYSTALLIZED STRUCTURE

FIGURE 13 LAND AREA STRUCTURE AFTER 26,410 ROUNDS

FIGURE 14 CRACK DEVELOPMENT AND INTERSECTION AFTER EXTENSIVE FIRING IN 7.62MM INSERT

FIGURE 15 SURFACE AREA STRUCTURE OF CALIBER .50 INSERT AFTER FIRING

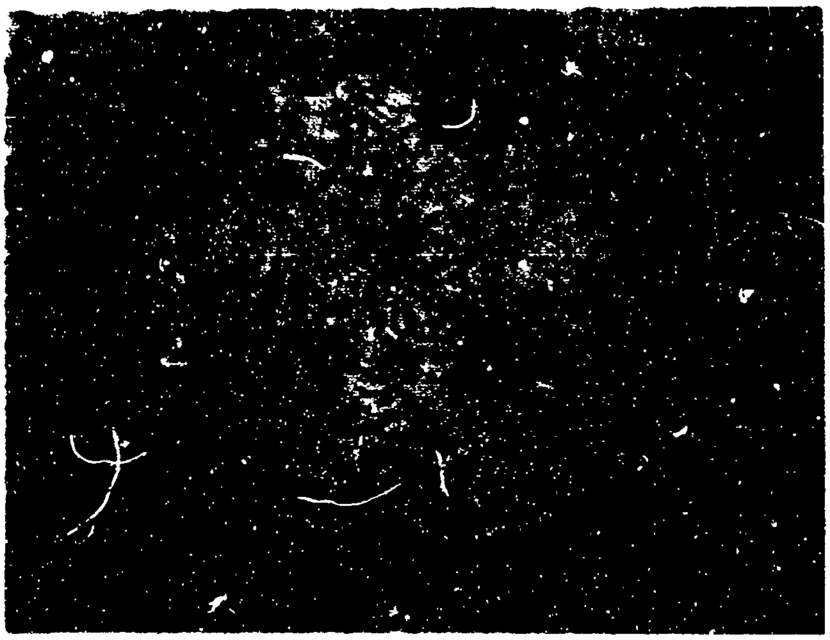

FIGURE 16 PHOTOMICROGRAPH SHOWING STRUCTURAL ALTERATION IN CALIBER .50 INSERT

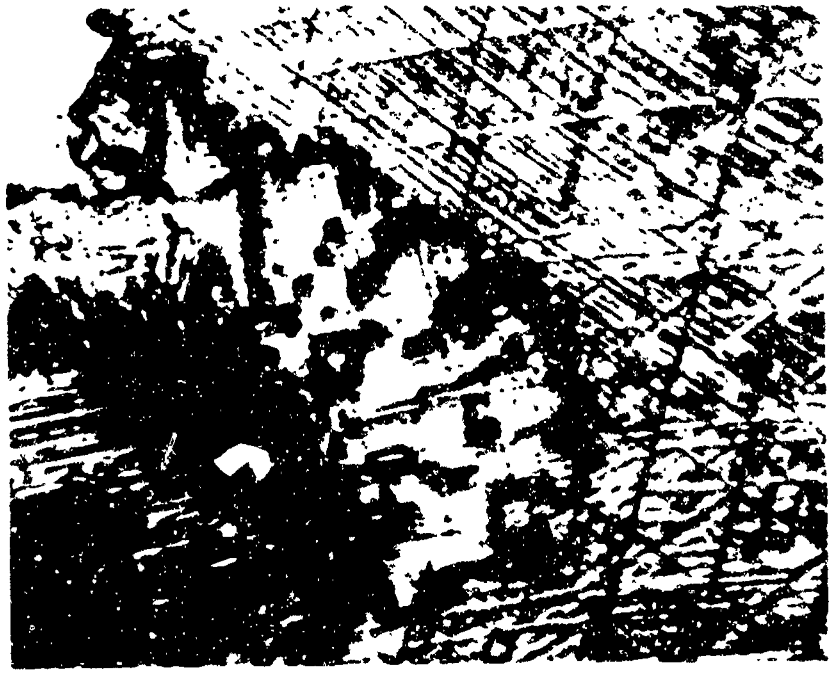

FIGURE 17 MICROSTRUCTURE EXHIBITING DEFORMATION BANDS IN THE LAMELLAR AREAS OF CALIBER .50 INSERT

FIGURE 18 LOW ANGLE SURFACE PROFILE SECTION SHOWING EXTENSIVE CRACK DEVELOPMENT IN 20MM INSERT AFTER 7170 ROUNDS

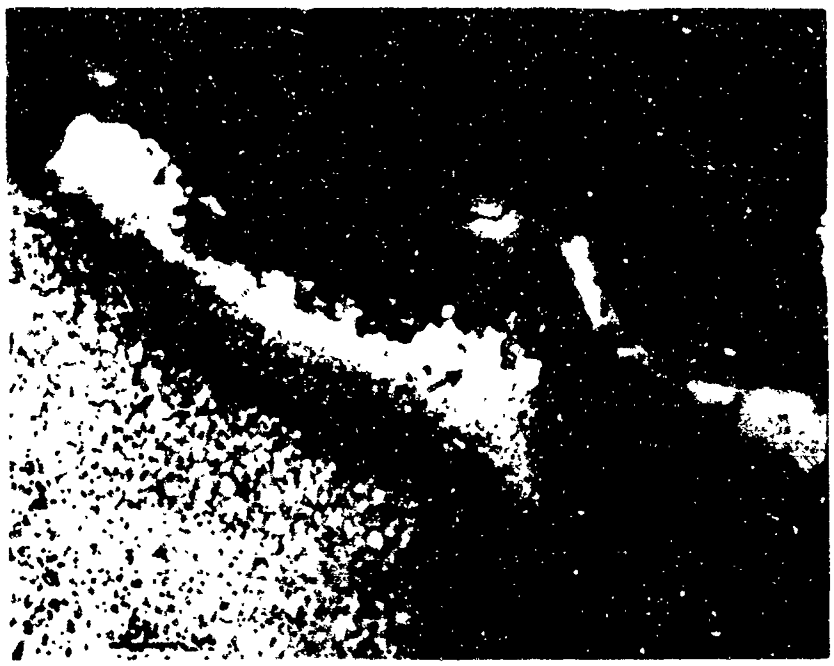

FIGURE 19 SURFACE LAYER STRUCTURE IN 20MM INSERT AFTER 7.70 ROUNDS

FIGURE 20 LONGITUDINAL SECTION SHOWING CRACK PROPAGATION IN 20MM INSERT AFTER 7170 ROUNDS

NOT REPRODUCIBLE

FIGURE 21 CHANGES IN CRACK TIP ORIENTATION FOR 20MM INSERT

LITERATURE CITED

1. Wissler, W. A., OSRD 6487, Report 417, Union Carbide and Carbon Research Laboratories, Inc., January 17, 1946.

2. Kotval, P. S., Trans. AIME, 1968, Vol. 242, p. 1951.

3. Wheeton, J. W., and R. A. Signorelli, Trans. ASM, 1955, Vol. 47, p. 815.

4. Buckley, D. H., "Adhesion of Cold Welding of Materials in Space Environment," ASTM STP 431, p. 248, Am. Soc. Testing Mats., Baltimore, Md., 1967.

5. Laird, C., "Fatigue Crack Propagation," ASTM STP 415, p. 131, Am. Soc. Testing Mats., Baltimore, Md., 1967.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of Robert D. Busch in the metallographic work and also the contributions by other members of the Laboratory. The data presented in this report will be utilized in an overall program initiated in the Science and Technology Laboratory to advance small caliber gun barrel technology.

APPENDIX A

I. SCHEDULE A

a. 100-round burst at 650 rpm
b. Cool for 2 minutes
c. Repeat a and b until 500 rounds are fired, cool to room temperature
d. Repeat c until 3000 rounds are fired

II. SCHEDULE B

a. 250-round burst at 1000 rpm
b. Cool for 10 minutes
c. Repeat a and b until 750 rounds are fired, cool to room temperature
d. Repeat schedule c to the point of necessary withdrawal of gun barrel

III. SCHEDULE C

a. 83- (or 84) round burst at 1000 rpm
b. Cool for 10 minutes
c. Repeat a and b until 250 rounds are fired
d. Cool for 10 minutes
e. Repeat c and d until 1000 rounds are fired
f. Repeat e to the point of necessary withdrawal

IV SCHEDULE D

1. a. 13-round burst at 60 rpm
   b. 10 second cool
   c. Repeat a and b to 26 rounds total
   d. 4-12 round burst with two second cooling interval between bursts followed by a 20-second cool
   e. Repeat d followed by 20-second cool
   f. Repeat e
   g. Cool entire barrel to room temperature

2. Fire three schedules of 1 (steps a through g)

3. Repeat test cycle (three schedules of 1) 19 times

APPENDIX B

Ammunition

7.62mm:	NATO M80, ball	
	velocity:	2750 fps
	pressure:	50,000 psi (avg. max.)
caliber .50:	M2, Ball	
	velocity:	2810 fps
	pressure:	55,000 psi (avg. max.)
20mm:	M206	
	velocity:	3460 fps
	pressure:	49,500 psi (avg. max.)

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Weapons Command Research & Engineering Directorate Rock Island, Illinois 61201	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

STRUCTURAL STABILITY OF A CAST Co-Cr-Mo ALLOY DURING IMPULSIVE THERMAL-MECHANICAL LOADING (U)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

William T. Ebihara

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1970	33	5

8a. CONTRACT OR GRANT NO. b. PROJECT NO DA 1T061102B32A c. AMS Code 5018.11.85500.01 d.	9a. ORIGINATOR'S REPORT NUMBER(S) RE-70-197 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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13. ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Cast cobalt alloy insert liners						
2. Gun barrel materials						
3. Thermal-mechanical fatigue						
4. Plastic deformation						
5. Microstructural alterations						

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